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NASA THERMIONIC-CONVERSION PROGRAM

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Abstract

The NASA applied research and technology (ART) program for thermionic energy conversion (TEC) is progressing effectively: Current out-of-core emphases allow converter material and design freedoms previously prohibited by in-core nucleonic and geometric restrictions. As a result, potential improvements indicate possibilities for severalfold increases in efficiencies. The new TEC-ART program concentrated initially on low-work-function collectors and interelectrode-loss reduction and revealed much in a short time. For example, arc-drop studies verified the necessity of stable emitters that operate well with little or no adsorbed cesium (NASA TM X-71549 and 1974 IEEE Plasma Science Conference). This new emission capability coupled with improved collectors that maintain performance with emitter-vapor deposit accumulations are requisites for efficient, enduring thermionic converters. The accomplishments and contributors in these areas are the subject of this paper.

FUTURE THERMIONIC-ENERGY-CONVERSION APPLICATIONS

NASA and ERDA cooperate in an applied-research-and-technology (ART) program to advance thermionic energy conversion (TEC). This coordinated work aims primarily at some of the more important applications and energy sources like those indicated in figure 1. As figure 1 suggests NASA and ERDA have programmatic goals that sometimes coincide. But they guard against wasteful duplication in detailed project objectives.

FIG. 1: ENERGY SOURCES FOR THERMIONIC CONVERSION

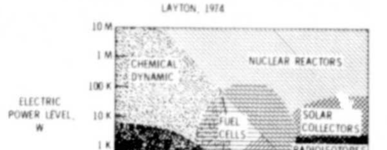
EARTH (ERDA)
- NUCLEAR (POWERPLANT TOPPING, REMOTE GENERATORS: UNDERSEAS, ETC. . . .)
- CHEMICAL (TOPPING CONVENTIONAL POWERPLANTS, BOTTOMING MHD, SMALL GENERATORS: LIQUID OR GASEOUS FUELS)
- CONCENTRATED SOLAR (THERMAL-STORAGE COMPLICATIONS)

SPACE (NASA)
- NUCLEAR (HIGH-POWER, LONG-LIFE: ORBITAL OPERATIONS, LEO TO GEOSYNCHRONOUS OR ESCAPE, INTERPLANETARY)
- ISOTOPIC (LOW-POWER, LONG-LIFE)
- CONCENTRATED SOLAR (CONTINUOUSLY SUN-SEEING ORBITS ELIMINATE THERMAL-STORAGE PROBLEMS)
- CHEMICAL (SMALL AUXILIARY POWER SYSTEMS)

For space, energy-source applicabilities derive from analytic power-level, service-time envelopes illustrated in figure 2. As the patterned areas reveal, nuclear reactors rule unchallenged in the long-duration, multihundred-kilowatt section of figure 2. Also in that region, TEC offers a major advantage for space applications: high waste-heat-rejection temperatures, hence low radiator weights.

FIGURE 2
REGIMES OF SPACE POWER APPLICABILITY:
ELECTRIC POWER LEVEL VERSUS DURATION OF USE

LAYTON, 1974



So nuclear thermionic capability will become critically important for space missions requiring more than 100 kW_e. Figure 3 predicts such levels of space-power requirements in the late 1980's. Then--in about 10 years--system-ready nuclear thermionic power generators should be available. Time is short.

FIGURE 3
SPACE-POWER REQUIREMENTS FROM 1960 THROUGH 1990

Figures 4, 5, and 6 imply a consensus of international experts on the urgent need for nuclear TEC in space. The statements from NASA's Research and Technology Advisory Council (RTAC) and its Office of Aeronautics and Space Technology (OAST) Workshop also hint strongly of the desirability of heat-pipe-cooled reactors.

FIGURE 4: NUCLEAR THERMIONIC ENERGY CONVERSION

LAYTON RTAC COMMITTEE (APR 1975):

"RECOMMENDED THAT OAST CONTINUE & STRENGTHEN THERMIONIC RESEARCH & TECHNOLOGY EFFORTS . . . , SYSTEM STUDIES FOR SPACE APPLICATIONS CONCENTRATING ON OUT-OF-CORE . . . CONFIGURATIONS, & CRITICAL HIGH TEMP SYSTEM ELEMENTS SUCH AS INSULATORS & HEAT PIPES"

FIGURE 5
NUCLEAR THERMIONIC ENERGY CONVERSION

OAST WORKSHOP (AUG 1975)
- POWER WORKING GROUP: IDENTIFIED NUCLEAR THERMIONIC CONVERSION AS ONE OF THE "MAJOR ADVANCEMENTS IN POWER SYSTEMS TECHNOLOGY (THAT) MUST BE MADE IF THE OUTLOOK FOR SPACE & OTHER ADVANCED USER PLANS ARE TO BE ACCOMPLISHED"
- PROPULSION WORKING GROUP: FOR LOWEST "PAYLOAD DELIVERY COST" (3×10^3 \$/KG TO ΔV = 45 KM/SEC WITH 500 KG FOR EARTH ESCAPE) "THE PROPULSION APPROACH . . . IS A LIGHTWEIGHT MULTIHUNDRED KW FISSION REACTOR WITH THERMIONIC . . . CONVERSION PROVIDING ELECTRICITY FOR ELECTROSTATIC PROPULSION"
- THERMAL CONTROL WORKING GROUP: "NUCLEAR ELECTRIC POWER & PROPULSION FOR OVER 100 KWE MISSIONS . . . NEED LIGHTWEIGHT THERMAL-TRANSPORT SYSTEMS THAT HANDLE GREAT POWER DENSITIES AT HIGH TEMPS WITH SMALL THERMAL GRADIENTS. METALLIC-FLUID HEAT PIPES CAN MEET THESE REQUIREMENTS"

FIGURE 6: NUCLEAR THERMIONIC ENERGY CONVERSION

RUSSIAN PROGRAM (SEPT 1975 TRIPS BY U. S. SCIENTISTS):

- RADIOISOTOPE THERMIONIC GENERATOR TESTED (1971), IMPROVED
- TOPAZ-3 (6 KWE, 7760 HR ACCRUED)
- 10 KWE NUCLEAR THERMIONIC SPACE CAPABILITY NOW
- NEW HIGH-PERFORMANCE NUCLEAR THERMIONIC DESIGN IN PROGRESS
- HIGH SPACE POWER REQUIREMENTS WILL BE PROVIDED BY THERMIONIC REACTORS

The rationale for the second statement of figure 5, favoring electric propulsion powered by nuclear TEC, appears graphically in figure 7. Figure 8 shows an example of an electrically propelled spacecraft powered by a heat-pipe-cooled reactor energizing a TEC system.

FIGURE 7: COST FOR HIGH-VELOCITY PROPULSION

OAST SPACE TECHNOLOGY WORKSHOP, PROPULSION WORKING GROUP, 1975

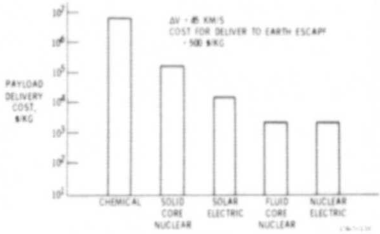


FIGURE 8

JPL-PROPOSED SHUTTLE-LAUNCHED MULTIMISSION SPACECRAFT
MULTIHUNDRED-KILOWATT THERMIONIC POWER GENERATION
HEAT-PIPE-COOLED REACTOR ELECTRIC PROPULSION

In addition to providing propulsion for acceleration from low earth orbits to geosynchronous ones or to escape, and for interplanetary missions, nuclear TEC should supply power for orbital operations, for nuclear-waste-disposal runs, lunar bases, and large space stations.

Thus the NASA program is necessary to cope with future technological requirements and complexities that will eventually affect all lives on earth.

THE CURRENT NASA TEC-ART PROGRAM

Providing the capability to produce efficient, durable, economical thermionic converters is a major objective in NASA's program. And as figure 9 indicates, various space missions and terrestrial applications can utilize TEC over its full range of practical operating temperatures. The lower section of figure 9 lists some general goals for attainment of full-range, high-efficiency TEC.

FIGURE 9

NASA THERMIONIC-ENERGY-CONVERSION (TEC)
APPLIED-RESEARCH-AND-TECHNOLOGY (ART) PROGRAM

FULL-RANGE, HIGH-EFFICIENCY TEC
- HIGH EMITTER & COLLECTOR TEMPS (HIGH-POWER SPACE APPLICATIONS: MINIMAL RADIATOR WEIGHTS)
- HIGH-EMITTER, LOW-COLLECTOR TEMPS (APPLICATIONS WHERE WASTE-HEAT-ELIMINATOR WEIGHTS ARE NOT CRITICAL)
- LOW EMITTER & COLLECTOR TEMPS (TERRESTRIAL APPLICATIONS IN HOT-CORROSIVE ATMOSPHERES)
- PROBABLE GENERAL TEMP RANGES, K:
  - EMITTERS: 1200 TO 1800
  - COLLECTORS: 400 TO 1000
  - RESERVOIRS: DEPENDENT ON PLASMA-LOSS-REDUCTION REQUIREMENTS & ELECTRODE EFFECTIVENESS

GENERAL TEC-ART GOALS
- SIGNIFICANT DECREASES IN ARC DROPS
- DIMINISHED COLLECTOR WORK FUNCTIONS WHERE REQUIRED
- EFFECTIVE EMITTERS IN REDUCED CESIUM PRESSURES
- DURABLE EMITTER, COLLECTOR COMBINATIONS THAT MAINTAIN PERFORMANCES AGAINST VAPORIZATION, DEPOSITION EFFECTS

When integrated these improved elements must act coefficiently to produce greater converter efficiency, durability, and economy. The ultimate objective is not refinement of the separate components: It is mission-plan execution through on-design system performance because of effective thermionic conversion.

But efficient operation of any one converter at all temperatures is probably impractical. So NASA's program must allow specifically advantageous prescriptions for system optimizations throughout the full range of operating conditions for the gamut of appropriate space-power applications.

To contribute to the attainment of these goals NASA centers work in the areas outlined in figure 10.

FIGURE 10: NASA TEC-ART CENTERS

AMES RESEARCH CENTER (ARC)
- BASIC SURFACE RESEARCH

JET PROPULSION LABORATORY (JPL)
- MISSION & SYSTEM STUDIES
- SYSTEMS-TECHNOLOGY SUPPORT

LEWIS RESEARCH CENTER (LeRC)
- MANAGEMENT TEC-ART CONTRACTS & GRANTS
- CONVERTER R & T
- HEAT-PIPE R & T
- MATERIALS R & T

As figure 10 reveals, LeRC manages industrial contracts and university grants: The organizations and studies supported by NASA in this area appear in figures 11 and 12.

FIGURE 11: NASA TEC-ART CONTRACTS AND GRANTS

RASOR ASSOCIATES (RA)
- BASIC ADVANCED-CONVERTER-MODE EXPERIMENTS
- ANALYSIS & INTERPRETATION OF ADVANCED-MODE DATA
- RECOMMENDATION OF ADVANCED-MODE MATERIALS

THERMO ELECTRON CORPORATION (TECO)
- BASIC SURFACE EXPERIMENTS
- EXHANCED CONVERTER EXPERIMENTS
- HIGH-EFFICIENCY-CONVERTER EVALUATIONS

FIGURE 12: NASA TEC-ART CONTRACTS AND GRANTS

ARIZONA STATE UNIVERSITY (ASU)
- THERMIONIC EMISSION FROM PROMISING ELECTRODE MATERIALS

OREGON GRADUATE CENTER (OGC)
- FABRICATION OF MONOCRYSTALLINE THERMIONIC-CONVERTER ELECTRODES
- CHARACTERIZATION OF BEST SINGLE-CRYSTAL FACES

STATE UNIVERSITY OF NEW YORK AT BUFFALO (SUNY)
- UNIFIED THERMIONIC-CONVERTER PLASMA THEORY
- EXAMINATION OF IONIZATION-ENHANCEMENT MECHANISMS

UNIVERSITY OF MINNESOTA (UM)
- STUDY OF CESIUM-ION SPECIES IN THERMIONIC DIODES

Although the current program is comparatively small, these contributors are striving to provide the necessary performance gains and design information for NASA-mission requirements. As figure 13 re-emphasizes, this present acquisition of knowledge on internal components and processes must serve ultimately to optimize the converter in maximizing system effectiveness.

FIGURE 13

NASA TEC DESIGN CONSIDERATIONS

MAXIMIZE	OPTIMIZE	MINIMIZE
EFFICIENCY (SYSTEM)	EMISSION	RESISTIVE DROPS
LIFETIME	COLLECTION	THERMAL LOSSES
SIMPLICITY	IONIZATION	WEIGHT (SYSTEM)
		COST (SYSTEM)

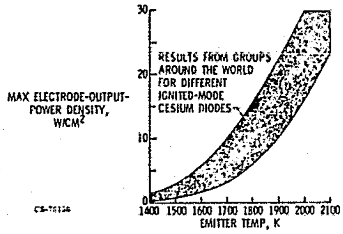
RECOGNIZE
- CARNOT: HOTTER EMITTERS & COLDER COLLECTORS YIELD HIGHER IDEAL THERMAL EFFICIENCIES
- IN-CORE RESTRICTIONS NO LONGER INHIBIT CONVERTERS
- MATERIALS DICTATE PERFORMANCE & DURABILITY:
  - BARE & CESIATED CONVERTER ELECTRODE CAPABILITIES;
  - ADDITIVE INFLUENCES;
  - THERMAL, PHYSICAL, & CHEMICAL COMPATIBILITIES;
  - VAPORIZATION, DEPOSITION EFFECTS
- MISSION & SYSTEM REQUIREMENTS PREDOMINATE
- HIGHER WASTE-HEAT-REJECTION TEMPS MEAN LIGHTER RADIATORS

The lower section of Figure 13 lists some observations pertinent to future design considerations. For example, as Figure 14 illustrates, higher cesium-diode emitter temperatures generally produce greater outputs. TECO's Hatsopoulos and Gyftopoulos also show in their 1973 book Thermionic Energy Conversion that optimum efficiencies rise in general with increasing emitter temperatures in the practical operating range. This principle should also prevail for anticipated high-performance converters because they too are basically Carnot devices. The much-heralded greatly improved TEC potentialities are not inherent advantages gained with lower temperatures, of course: These potential improvements redound from escaping in-core nucleonic and geometric restrictions and attaining the freedom of out-of-core electrode materials and configurations. As a result, converter "materials dictate performance and durability" now as never before. Some of the more important material implications appear in figure 13.

FIGURE 14

RELATION OF MAXIMUM POWER OUTPUT TO EMITTER TEMPERATURE

HATSOPOULOS & GYFTOPOULOS, 1973



The last of these several material effects, the vaporization, deposition problem, demands special attention in thermionic-converter work, where high-temperatures and surface phenomena prevail. Most TEC-ARTists worry about emitter-vapor deposits shorting out the insulators. So they provide line-of-sight or maze shielding to preclude such possibilities. But vaporization, deposition processes are also critically important to the collector because adsorption of only a fraction of an atomic monolayer can drastically change work functions and electron reflectivities.

The hot, close-up emitter practically covers the several-hundred-degrees-cooler collector. And the emitter vapor pressure is several orders of magnitude higher than that of an emitter-vapor deposit on the collector. So in low-pressure converters the arrival rate of emitter vapor on the collector is several orders of magnitude greater than the departure rate of its accumulated emitter-vapor deposit: This arrival-to-departure ratio approximates the actual emitter vapor pressure divided by its vapor pressure at the collector temperature with that quotient multiplied by the square root of the collector-to-emitter temperature ratio.

Thus emitter-vapor deposits in general tend to build up on collectors in thermionic converters. And observations like those of JPL's Rouklove in the August 1969 "IEEE Transactions on Electron Devices" verify this deduction. He noted "a slow deposition of emitter material occurs on the collector surface" and made the usual recommendation of a rather simple solution: "Because any initial advantage obtained by building the converter with dissimilar electrode materials will be eliminated by this deposition of emitter material on the collector, it is believed desirable to assemble converters using identical materials for the emitter and collector."

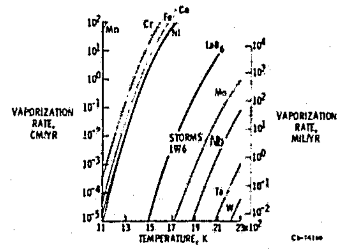
Thring expressed a similar viewpoint in the July 1975 "Chartered Mechanical Engineer": "For the anode BaO on W gives a very low work function but is liable to be poisoned by atoms evaporated from the cathode. The use of the same material (anode) as for the cathode, relying on the Cs layer, is therefore preferred in the interests of long life."

Other methods for coping with this vaporization, deposition effect are possible but exceptional. "Using identical materials for the emitter and collector" is simple and general.

Extrapolations of figure 15, with the recognition that an atomic monolayer is 10^{-8} to 10^{-7} cm thick, allow some estimates of the vaporization, deposition problem. But figure 15 most effectively implies the extreme limitations of stainless steels and superalloys as thermionic emitters compared with the capabilities of more refractory materials.

FIGURE 15

VAPORIZATION OF PURE METALS AND LANTHANUM HEXABORIDE



ASU's Jacobson in a recent NASA-grant report commented on this facet of the vaporization, deposition effect: "Problems that have arisen in attempts to measure accurately the emission from superalloys have been, first of all, that the evaporation rates are too high at reasonable temperatures, 1200°K to 1400°K.... The experience in this laboratory is that above 1200°K very heavy deposits of evaporated material have been found on the collector and guard ring."

As the previous discussions reveal, high operating temperatures complicate converter material problems. But as the first and last statements in the lower section of figure 13 recall, high temperatures also afford unique TEC advantages.

NASA TEC-ART ACCOMPLISHMENTS

Some recent major accomplishments in the NASA program and the primary contributors appear in figure 16:

FIGURE 16

NASA TEC-ART ACCOMPLISHMENTS

EXPERIMENTAL INTERELECTRODE-LOSS REDUCTIONS FOR LOW TEC OUTPUTS (RA)
GENERALLY HIGHER TEC EFFICIENCIES WITH LOWER-WORK-FUNCTION COLLECTORS (TECO)
EXPERIMENTAL CESIATED, OXYGENATED COLLECTORS WITH WORK FUNCTIONS LESS THAN 1.2 eV (TECO, JPL)
FIRST WORK-FUNCTION DETERMINATIONS FOR SINGLE-CRYSTAL METALLIC HEXABORIDES (MB_6) (OGC)
STABLE, EFFECTIVE EMITTERS FOR VERY LOW CESIUM PRESSURES (LeRC)
EMITTER, COLLECTOR COMBINATIONS FOR TEC VAPORIZATION, DEPOSITION EFFECTS (TECO: Cs, O, W; LeRC: MB_6)
DESIGN OF OUT-OF-CORE TEC SYSTEM FOR NUCLEAR ELECTRIC SPACE APPLICATIONS (JPL, LASL)
THEORIES TO GUIDE, DESCRIBE, & CORRELATE FUTURE WORK (RA, SUNY, TECO)

CS-76134

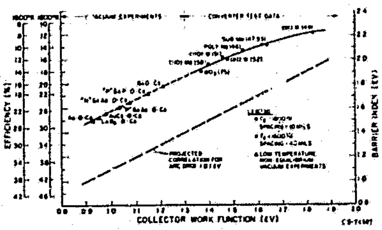
RA demonstrated reductions of interelectrode losses for low converter outputs. They are currently moving these benefits into the practical power-output regime.

TECO provided the data and correlations in figure 17 showing that lower collector work functions generally produce higher TEC efficiencies. This chart gives results for 1600K and 1800K emitters, exemplifying general efficiency gains with emitter-temperature increases. Figure 17 also indicates appropriate barrier indices, which are essentially sums of the collector work functions and their accompanying interelectrode losses.

Attainments by TECO and JPL of less-than-1.2 eV work functions for cesiated, oxygenated collectors further dramatize the importance of efficiency trends pictured in figure 17.

FIGURE 17

EFFECTS OF COLLECTOR WORK FUNCTION AND ARC DROP ON THERMIONIC CONVERSION EFFICIENCY (THERMO ELECTRON CORP.)



Note that a cesium (Cs), oxygen (O), lanthanum hexaboride (LaB_6) electrode system corresponds to a TEC efficiency of 36% for a 1600K emitter and a 0.1 V arc drop in figure 17. With 0.1 cm interelectrode gaps often advocated for future enhanced-converter operation LaB_6 vaporization appears acceptable for 1600K-emitter service according to the probable curve in figure 15. Furthermore the following paragraph depicts LaB_6 as a promising 1600K emitter even without adsorbed Cs; its work function diminishes, of course, with Cs adsorption. So an augmented converter with LaB_6 used for the emitter and collector in the presence of Cs with O as an additive looks like a good performer and a solution to the vaporization, deposition problem.

Pertinent work-function revelations come from OGC, where single-crystal characterization is underway for metallides with promise as TEC electrodes (NASA CR-2668). Swanson measured Richardson values for 100-plane work functions of approximately 2.47 eV for LaB_6 and 2.3 eV for cerium hexaboride (CeB_6). Such work functions correspond to emission of 5 A/cm^2 at 1600K for LaB_6 and at 1500K for CeB_6. The field-emission, retarding-potential (FERP) work function for LaB_6 is 2.28 eV. Moreover, field-emission tests reveal that other-than- 100 crystal planes of LaB_6 have even lower work functions. These are uncesiated emission characteristics indicating suitability for emitters of advanced converters using little or no cesium pressure. OGC reveals that cesiation reduces the work function of clean LaB_6 to less than 1.4 eV--even without optimization. And as TECO shows in figure 17, cesium and additive oxygen on LaB_6 produce work functions below 1.0 eV.

LeRC proposed such metallide materials as stable, effective emitters and good cesiated collectors (NASA TM X-71549 and 1974 IEEE Plasma Science Conference). And in addition to determining the monocrystalline characteristics of these materials, OGC will supply single crystals of each of the better metallide-electrode prospects for coefficient emitter and collector evaluation in the LeRC diminiode program.

The most highly developed example of emitter, collector combinations adaptable to withstanding vaporization, deposition effects is the TECO Cs, O, tungsten (W) thermionic diode. This electrode system offers demonstrated effectiveness. But as previously stated, some of the metallides proposed to serve simultaneously as emitters and collectors promise considerably improved converter performances too.

Predicted efficiency improvements prompted JPL and LASL to collaborate on a space-power system design utilizing a heat-pipe-cooled reactor with out-of-core thermionic conversion. This proposed version, pictured in figure 8, relies on uranium-dioxide fuel and on molybdenum-alloy construction on the hotter side of the converter. The "expected mass for the power subsystem is approximately 17 kg/kW$_e$ for power levels of 400 kW$_e$ or larger." And that promising specific mass resulted from using relatively conservative TEC-efficiency predictions.

These gratifying results, outlined in figure 16, indicate good potentialities for attaining important NASA TEC-ART objectives: The basic surface and plasma studies, converter demonstrations, and system analyses are progressing well for the program size. In addition overall theories are evolving to correlate, describe, and guide experimental and developmental work. The primary theoretic contributors under NASA and ERDA auspices are RA, SUNY, TECO, and Princeton.

Unfortunately figure 16 does not list the important contributions in support technologies like those for structural and protective materials, heat pipes, and advanced fabrication and processing techniques and equipment. However, significant implementing gains are always essential for primary programmatic breakthroughs. These necessary, yet unspectacular secondary accomplishments absorb time, talent, and money too. And a detailed integration of all such required growth increments would be massively more impressive than this limited view of the peaks of the TEC-ART topography. But length restrictions inhibit the present program review.

In any event the base for a new enlightened and sophisticated approach to thermionic conversion is being effectively laid. After this initial technological build-up, important results should come in greater numbers and shorter times.